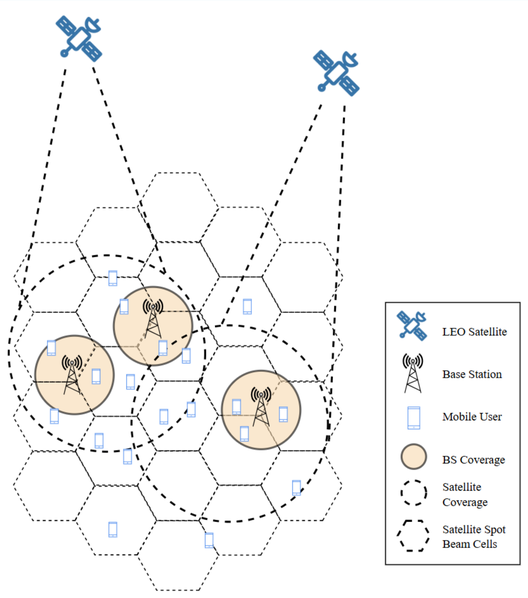
User Association for Satellite-Terrestrial Integrated Networks with Multiple Base Stations and Spot Beam LEO Satellites

Changgyu Lee and Mai Vu
Department of Electrical and Computer Engineering, Tufts University

Tufts University
School of Engineering
Electrical and Computer Engineering

INTRODUCTION



Motivation

- The Satellite–Terrestrial Integrated Network (STIN) is a technology that integrates and exploits the advantages of both networks
- Modern LEO satellites utilize spot beams to communicate with users
- Current literature often studies either spot-beam LEOs without terrestrial integration or STINs without realistic beam models

Contribution

- We propose a **practical STIN system** with multiple spot beam LEO satellites
- We optimize user association to **minimize delay under data-volume constraints** while also addressing feasibility issues

System Model

- Multiple terrestrial BSs each with multiple antennas
- Multiple LEO satellites with **multiple spot beams**
- Multiple single-antenna ground users that can communicate with either a satellite or a BS
- STDMA/TDMA multiple access

PROBLEM STATEMENT

Minimize total delay by optimizing user associations:

$$\min_{\alpha,\beta} \sum_{t=1}^{T} \left(\tau^p(t) + \tau^c(t) \right)$$

$$\text{s.t.} \quad \mathbf{A}_m(t)\mathbf{1}_K \preceq \mathbf{1}_L \quad \text{for } \forall m,t$$

$$(\mathbf{B}(t))^T \mathbf{1}_K \leq \mathbf{N}_J \quad \text{for } \forall t$$

$$\sum_{m=1}^{M} (\mathbf{A}_m(t))^T \mathbf{1}_L + \mathbf{B}(t)\mathbf{1}_J \preceq \mathbf{1}_K \quad \text{for } \forall t$$

$$\alpha_{k,l,m}(t), \beta_{k,j}(t) \in \{0,1\} \quad \text{for } \forall k,j,l,m,t$$

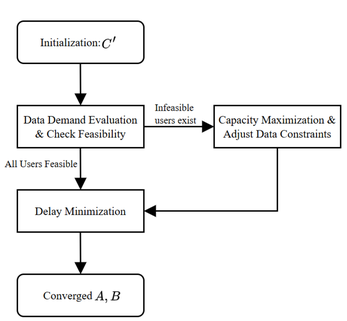
$$\sum_{t=1}^{T} \left(W_S R_k^S(t) + W_B R_k^B(t) \right) \tau_0 \geq C_k \quad \text{for } \forall k$$

- BSs and spot beams have maximum supportable users per time slot
- Each user connects to either a BS or a satellite spot beam
- Data-volume constraints must be satisfied

PROPOSED SOLUTIONS

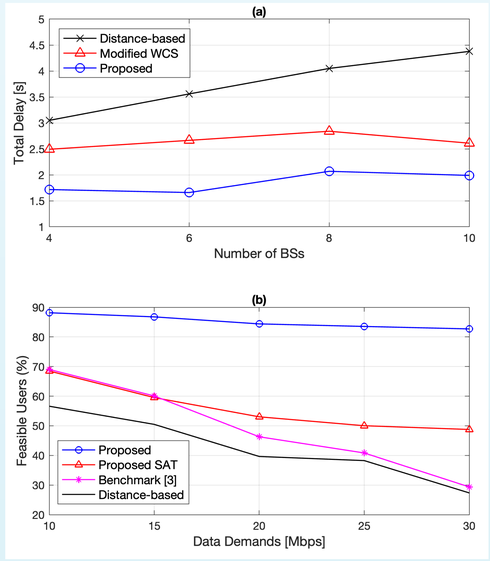
- To solve the NP-hard **MINLP delay minimization problem with data volume constraints**, we propose an algorithm with the multiple steps.
- Additionally, we also address the **feasibility of practical pre-given data-volume constraints**.

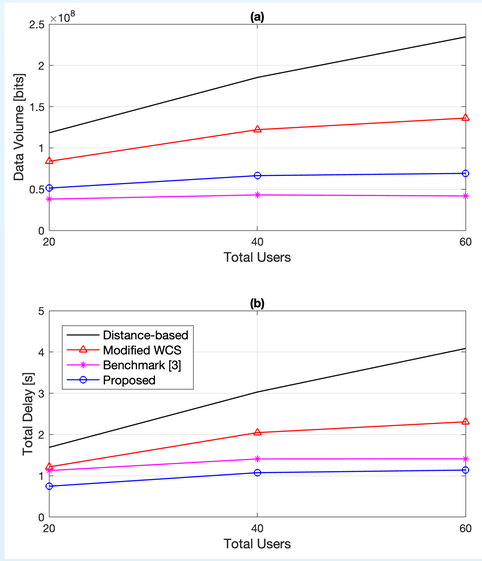
The optimization process works as follows.



1. Initialize with a data volume from modified worst case swapping (WCS) [1] and check data demand feasibility.
2. If infeasible, handle data demands via weighted sum-rate maximization with Dirichlet-sampled weights.
3. If feasible, reformulate problem as a convex MIP via quadratic transform [2].
4. Iteratively update association and auxiliary variables.
5. Apply local shuffle to escape local optima.

RESULTS

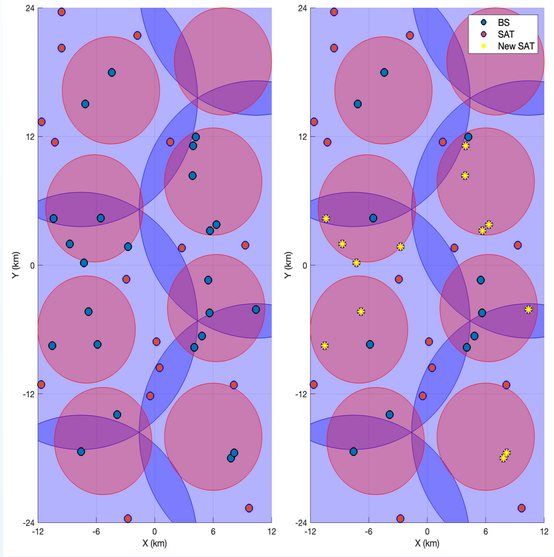




Key Observations:

- The results show robustness of the proposed algorithms under varying data demand and number of users
- The delay-minimization algorithm effectively reduces total delay for varying numbers of BSs
- Terrestrial network integration can satisfy higher user data demands
- **Benchmark comparison:** with spot beam satellite system [3]
  - Our feasibility evaluation algorithm better satisfies user demands
  - Our delay minimization algorithm delivers higher data volumes while meeting constraints, with low total delay
- Other algorithms fail to reduce delay effectively, as integrated terrestrial networks add unnecessary data volume

CONCLUSION



- We proposed a user-association algorithm for spot beam based STINs
- Our algorithm minimizes total delay under data-volume constraints
- Proposed algorithm achieves low delay and robust performance across scenarios
- It can also ensure feasibility under practical data demands via capacity maximization
- Integrating terrestrial BSs further improves feasibility in meeting user demands

REFERENCES

[1] A. Alizadeh and M. Vu, "Load balancing user association in millimeterwave mimo networks," IEEE Transactions on Wireless Communications, 2019

[2] K. Shen and W. Yu, "Fractional programming for communication systems—part i: Power control and beamforming," IEEE Transactions on Signal Processing, 2018.

[3] L. Lei et al, "Spatial-temporal resource optimization for uneven-traffic leo satellite systems: Beam pattern selection and user scheduling," IEEE Journal on Selected Areas in Communications, 2024.

Acknowledgments: This work was supported in part by the National Science Foundation under SWIFT grant 2127648.